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Juniper, Pinyon, Oak, and Mesquite Volume Equations for Arizona

David C. Chojnacky

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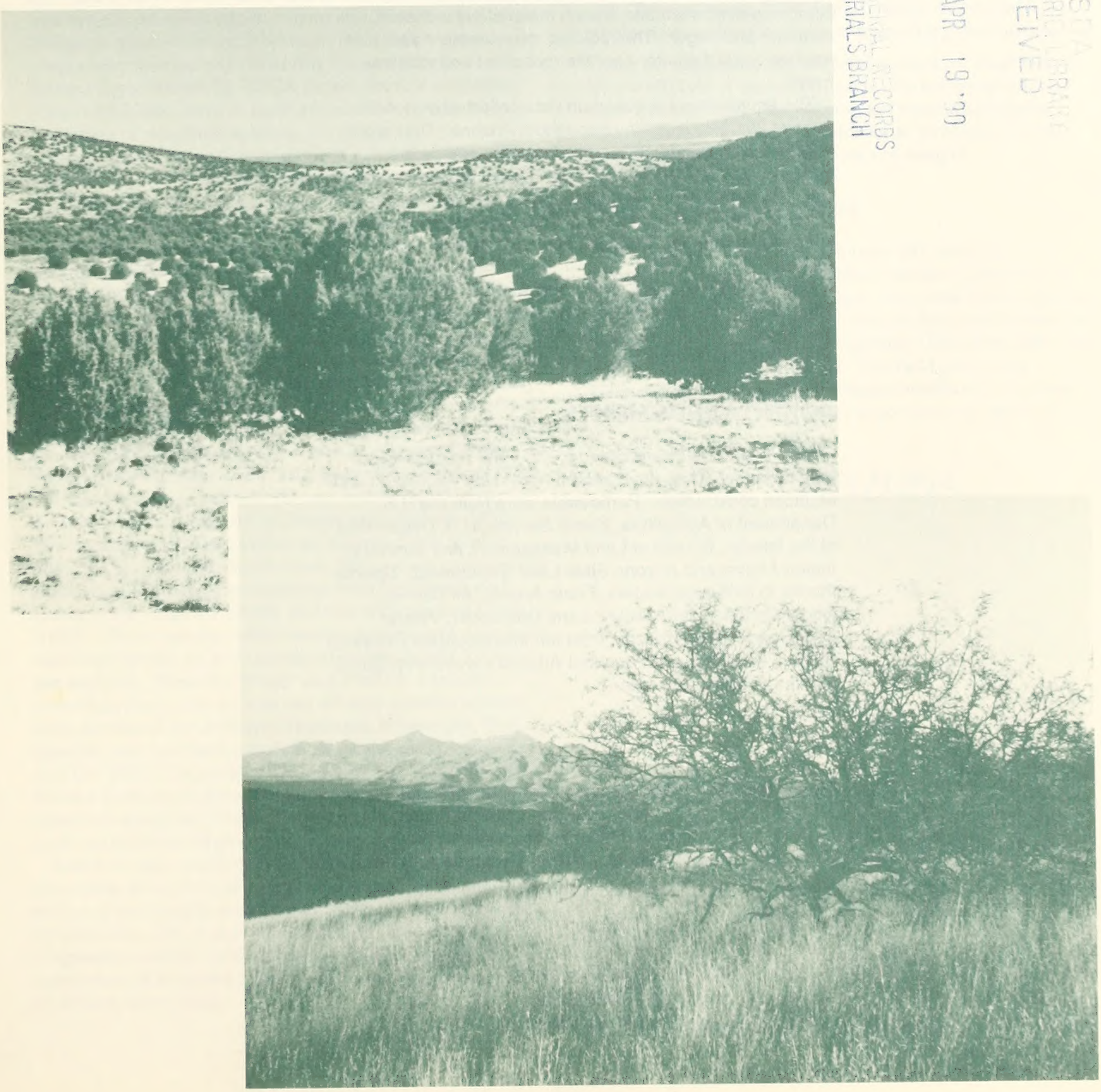

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RESEARCH SUMMARY

Cubic foot volume equations have been developed for Arizona's juniper, pinyon, oak, and mesquite species. Volume predictions can be obtained for wood and bark combined of all stem and branch material 1.5 inches in diameter and larger. The required measurement variables are tree basal diameter near the root collar and total tree height.

The equations were based on data collected on 1,442 trees at 291 field locations throughout Arizona. Data were collected on all woodlands owned or managed by the following: State of Arizona; private individuals and corporations; Papago, Hopi, and Kaibab Indian Reservations; Coronado and Prescott National Forests; all Arizona Bureau of Land Management Districts; and several other public entities.

Results are presented in equation and tabular formats. Volume equation construction and equation reliability are discussed. Graphs display results compared to those from other available Arizona woodland volume studies.

ACKNOWLEDGMENTS

Many individuals contributed to the 1985 Arizona woodland inventory. They provided the necessary data for volume equation construction. Participants were from the U.S. Department of Agriculture, Forest Service; U.S. Department of the Interior, Bureau of Land Management and Bureau of Indian Affairs; and Arizona State Land Department. Special thanks to field crew leaders, Frank Angele, Ali Conner, Roger Conner, Claire Dailey, Larry DeBlander, Valerie Kalve, and Robert Rhoads, from the Intermountain Research Station, who trudged throughout Arizona's woodlands for 10 months to collect the data.

Cover photos: Upper: One-seed juniper above Chino
Valley, Prescott National Forest.
Lower: Mesquite across valley from Santa
Rita Mountains, Coronado National Forest

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INTRODUCTION

Arizona supports vast and diverse juniper, pinyon, oak, and mesquite woodland forests. Much of northern Arizona contains juniper-pinyon woodlands. In the central part of the State and on the lower slopes of the southern mountain ranges, an oak-juniper-pinyon woodland thrives. Mesquite woodlands occur between the southern mountain ranges interspersed with Sonoran Desert and grasslands. Arizona's woodlands, by USDA Forest Service definition (USDA FS 1985), have at least 10 percent crown coverage from trees of woodland species.

Recent economic and management needs for information on Arizona's woodlands prompted an extensive inventory in 1985 (USDA FS 1985). Primary objective was to determine total woodland tree volume. Because direct woodland volume measurement is time consuming and costly, data were collected in the inventory on a subsample of trees for later volume equation development. This paper reports on volume equations constructed from that data.

Previous efforts to develop volume equations for pinyon and juniper species revealed that basal diameter, crown dimensions, total height, and number of basal stems are important predictor variables of tree volume (summarized in Chojnacky 1985). Similar results have also been found for oak and mesquite woodland species (Gronski 1987; Pillsbury and Kirkley 1984; Whisenant and Burzlaff 1978).

Juniper, pinyon, and oak volume estimation specific to Arizona was summarized by Barger and Ffolliott (1972). They published volume tables for pinyon, Utah juniper, alligator juniper, and Gambel oak. These were produced by modifying, extending, or adapting work by Howell and Lexen (1939), Howell (1940), and Gevorkiantz and Olsen (1955). These volume tables require total height and basal diameter for pinyon or diameter at breast height for juniper and oak. Since the Barger and Ffolliott summary, several juniper, pinyon, and oak volume equations have been developed for Arizona's Hualapai, Havasupai, Fort Apache, and San Carlos Indian Reservations (Chojnacky and Ott 1986; Chojnacky 1988). These equations predict volume from basal diameter and total height. For Arizona's mesquite, Olson (1940) and Andrews (1988) each constructed volume equations from basal diameter.

Based on past woodland volume work in Arizona and elsewhere, some form of tree diameter measurement and total tree height are the most common volume predictor variables. From previous work (Chojnacky 1985; Chojnacky and Ott 1986), three principles relating the importance of diameter and height to woodland volume prediction seem clear:

1. Volume is adequately predicted from the combination variable, diameter squared times height divided by 1,000 (DSQH).
2. The volume-to-DSQH relationship is linear, except for the largest trees.
3. The volume-to-DSQH relationship differs between single-stem and multiple-stem trees of a given species.

These principles are not surprising, because they follow from well-known mensuration results for many tree species. Because they also reflect past woodland volume results from other studies, additional strategies for volume equation construction were not sought.

DATA COLLECTION

Volume data were collected from 291 plots (fig. 1) owned or managed by the State of Arizona; private individuals or corporations; Papago, Hopi, and Kaibab Indian Reservations; Coronado and Prescott National Forests; all Arizona Bureau of Land Management Districts; and some miscellaneous public entities. The field plots were subsampled from the 1985 Arizona woodland inventory (USDA FS 1985). Plots were proportionately selected

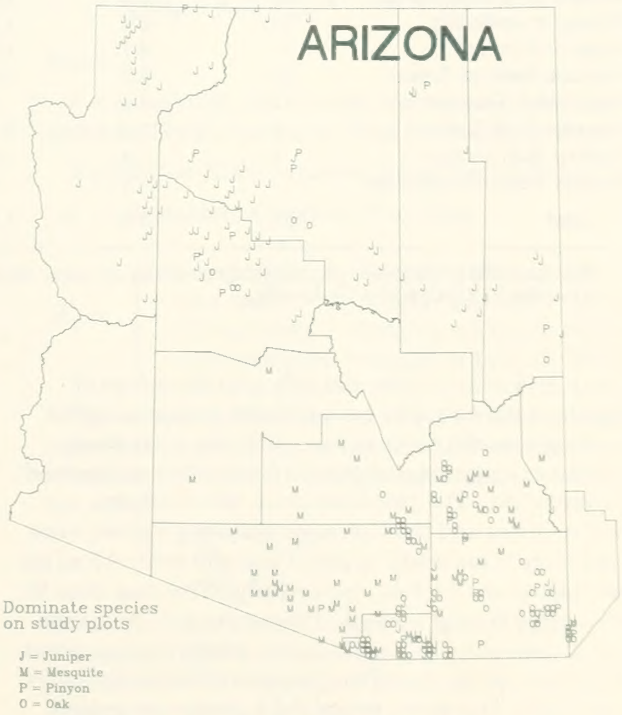

Figure 1—Location map of the 291 study plots.

Table 1—Summary of Arizona woodland volume data by species group

Ownership or management agency	Number of trees	Mean volume	Median volume	Mean DRC	Mean height	Single-stem trees	Number of plots[1]
		Ft³	*Ft³*	*Inches*	*Feet*	*Percent*	
			Juniper species group				
Private or corporate	169	7.5	2.4	12.0	12	41	37
Arizona Strip BLM District	91	8.4	2.7	11.4	13	68	20
Coronado National Forest	88	6.5	2.9	11.3	14	58	50
State of Arizona	83	10.7	5.2	13.8	14	43	17
Prescott National Forest	75	6.9	1.6	9.9	13	64	15
Phoenix BLM District	23	3.7	1.3	10.0	10	35	5
Hopi Indian Reservation	11	7.9	5.9	13.8	12	64	4
Kaibab Indian Reservation	5	9.4	6.0	11.6	19	100	1
Total	545	7.8	2.6	11.7	13	52	149
			Mesquite species group[2]				
State of Arizona	120	2.9	1.4	8.2	11	35	23
Papago Indian Reservation	67	2.5	1.2	7.0	12	46	16
Coronado National Forest	55	4.2	1.0	8.1	12	55	13
Private or corporate	49	1.8	0.8	7.4	10	39	9
Safford BLM District	19	1.5	1.0	8.0	8	21	5
Other public	6	1.1	.6	5.8	11	50	1
Phoenix BLM District	5	1.4	1.3	5.8	13	40	1
Total	321	2.7	1.2	7.7	11	41	68
			Oak species group				
Coronado National Forest	298	3.5	1.8	9.0	12	62	99
Private or corporate	31	7.0	2.6	10.1	16	48	9
Prescott National Forest	10	4.7	3.2	10.0	16	30	4
Safford BLM District	8	1.1	.5	6.6	9	50	2
State of Arizona	2	12.1	12.1	12.4	14	100	1
Other public	1	76.4	76.4	26.6	35	100	1
Total	350	4.0	1.8	9.1	13	60	116
			Pinyon species group				
Coronado National Forest	76	2.5	1.3	7.1	13	95	37
Arizona Strip BLM District	32	3.3	1.1	7.2	14	100	14
Private or corporate	32	2.7	1.0	7.0	13	88	12
State of Arizona	31	4.7	1.7	7.8	14	94	9
Prescott National Forest	25	3.2	1.6	6.6	17	100	9
Hopi Indian Reservation	13	1.8	.6	6.8	11	100	4
Phoenix BLM District	9	12.6	2.4	10.1	17	89	4
Safford BLM District	5	.8	.5	5.1	11	100	2
Kaibab Indian Reservation	3	1.6	.2	5.5	13	100	1
Total	226	3.3	1.2	7.2	14	95	92

[1] Because more than one species group occurred on many plots, summation of totals exceeds the total number of study plots.
[2] Includes 12 *Olneya* and 19 *Acacia.*

from map grid points systematically established on all woodlands of the owner or management groups sampled.

Resulting sampling intensities, with two exceptions, were about one plot located every 15 miles across the land base inventoried. The two exceptions, the southern Arizona counties and the Coronado National Forest, were sampled more intensively at about one plot every 10 miles and one plot every 3 miles, respectively. This was done to ensure a large enough sample of mesquite and evergreen oak trees. Sampling intensities were established on maps, and only those plots supporting woodland vegetation were field sampled. Therefore, actual field plots were spaced out much farther than the initial sampling grid because of many nonwoodland inclusions within the land base inventoried. Field plot size was 0.2 acre when crown cover of the surrounding stand was less than 30 percent, and 0.1 acre when crown cover was more than 30 percent. On each plot, about six trees (four for the Coronado) were randomly selected from three diameter classes, 3.0 to 9.9, 10 to 18, and >18 inches diameter at root collar (DRC).

Volume estimation was done using visual segmentation, a nondestructive method of counting the numbers of wood segments within a tree (Born and Chojnacky 1985). Wood segment dimensions were determined by dividing tree stems and branches into 1- to 6-foot length sections using 2-inch diameter classes. Some segment dimensions in lower portions of trees were measured, but most were estimated by sight. Cubic foot volume was computed for each segment using Huber's log formula (Husch and others 1982, p. 101). For each tree, segments that included wood and bark of all stems and branches larger than 1.5 inches in diameter were summed into a gross cubic foot volume. Both live and dead wood were included.

Other tree variables measured for volume equation development were total height, DRC, and number of basal stems. For trees forking at the root collar, an equivalent diameter (EDRC) was calculated for use in place of DRC:

$$\mathrm{EDRC} = \sqrt{\sum_{i=1}^{n} D_i^2} \tag{1}$$

where

n = number of basal stems 1.5 inches or larger

D_i = basal diameter of each stem.

Species sampled, followed in parentheses by numbers sampled, were *Juniperus osteosperma* (Torr.) Little (266), *J. monosperma* (Engelm.) Sarg. (169), *J. deppeana* Steud. (95), *J. erythrocarpa* Cory (15), *Pinus edulis* Engelm. (123), *P. cembroides* Zucc. (72), *P. edulis* var. *fallax* Little (31), *Prosopis velutina* Woot. (290), *Acacia greggii* Gray (19), *Olneya tesota* Gray (12), *Quercus emoryi* Torr. (85), *Q. arizonica* Sarg. (37), *Q. hypoleucoides* A. Camus (23), *Q. oblongifolia* Torr. (17), *Q. gambelii* Nutt. (5), and 183 combined *Quercus* hybrids, *Q. turbinella* Greene, *Q. chrysolepis* Liebm., and perhaps a few other evergreen oaks. For initial analysis, species were combined by genus, except for *Prosopis*, *Acacia*, and *Olneya*, which were combined into a mesquite group (table 1).

MODELING

Volume was compared to the combination variable, DRC or EDRC squared times height divided by 1,000 (DSQH), and other data characteristics through graphing. This was done to examine the volume data for differences among species and to examine the volume-to-DSQH relationship.

Little evidence was found to separate the data beyond juniper, oak, pinyon, and mesquite species groups. Either a species was represented by too few trees or species volume variation within a group was similar for all species. Visual volume estimation was considered a possible source of variation masking differences between species. Even though visual volume estimation was shown adequate for constructing volume equations (Born and Chojnacky 1985), no validation checks were available to confirm the reliability of the Arizona data. Some mesquite volume data from Pima and Santa Cruz Counties showed less variation in data estimated by one individual than in data estimated by several field crews combined. This probably suggests that visual volume estimation error should be considered if there is a need to identify precise volume relationships between individual species.

Graphs comparing the volume-to-DSQH relationship for all species groups supported the idea that volume can be adequately predicted from DSQH, even though the model relationship tends to change for larger trees. The graphs also showed the volume relationship differed slightly between single-stem and multiple-stem trees.

The point of change in the volume relationship between small and large trees was identified from graphs. Trees for each species group were ranked from smallest to largest, and the point of change was observed between the 90th and 95th percentile, corresponding to DSQH values of 6, 4, 3, and 2 for juniper, oak, pinyon, and mesquite, respectively.

An analysis of variance to test for differences within species groups was done to compare data from northern Arizona counties with data from southern Arizona counties (Chojnacky 1985, p. 5; Graybill 1976, p. 247). All four species groups showed no significant difference between northern and southern Arizona data (F-test significance levels were 0.19 or greater).

Based on the results of the graphical analysis and analysis of variance, volume equations were constructed for seven categories:

1. Single-stem juniper
2. Multiple-stem juniper
3. Single-stem oak
4. Multiple-stem oak
5. Single-stem mesquite
6. Multiple-stem mesquite
7. Single-stem pinyon (with 11 multiple-stem trees included).

The model was broken into two parts to allow for differences between the largest trees and the rest:

$$V = \begin{cases} \beta_0 + \beta_1 X + \beta_2 X^2 & \text{for } X < X_0 \\ \beta_3 + \beta_1 X + \beta_4 / X & \text{for } X > X_0 \end{cases} \tag{2}$$

where

V = gross cubic foot volume of wood and bark from all stems and branches larger than 1.5 inches in diameter

X = DRC or EDRC squared times height divided by 1,000

β_i = parameters estimated from data

$$X_0 = \begin{cases} 6 \text{ for juniper} & \text{(roughly a 20-inch DRC)} \\ 4 \text{ for oak} & \text{(roughly a 16-inch DRC)} \\ 3 \text{ for pinyon} & \text{(roughly a 12-inch DRC)} \\ 2 \text{ for mesquite} & \text{(roughly a 12-inch DRC)} \end{cases}$$

The two-part volume model was conditioned to be both smooth and continuous at the point where the two equations meet. This was done by imposing two restrictions on the model:

$$\beta_3 = \beta_0 + 3\beta_2 X_0^2 \tag{3}$$

$$\beta_4 = -2\beta_2 X_0^3 \tag{4}$$

The restrictions were obtained by equating the two parts of equation 2 for X equal to X_0, and by equating the first derivative of the two parts of equation 2 at the point X equal to X_0. Parameters for the two-part model (eq. 2) were determined using weighted regression with DSQH raised to the –1.5 power as the weight (Schreuder and Anderson 1984).

Several steps were used to obtain final volume model parameters. After the first regression, Cook's-D influence statistics (Cook 1977) were examined. Using criteria suggested by Belsley and others (1980, p. 29), Cook's-D values corresponding to each tree's volume were arrayed by species group. Trees above gaps in the upper tails of the distributions were identified. Further examination of these data showed inconsistencies in visual volume segmentation application for about half the cases, suggesting some data should be deleted.

Additional parameter estimates were then obtained after deleting data exceeding a given Cook's-D value. After several comparison trials, a Cook's-D value of 0.10 was chosen as a reasonable cut-off point, resulting in deletion of 20 trees. Reducing the Cook's-D cut-off point below 0.10, and deleting more trees, had a diminishing effect on parameter estimation. Final model parameters and tabulated volume predictions are given in the appendix in tables 3, 4, 5, and 6.

MODEL RELIABILITY

Results of regression goodness-of-fit analyses are summarized in table 2. The coefficient of determination (R^2) was computed using the regression weights and computed again without regression weights. Neither computation method was completely satisfactory because the weighted R^2 was based on a rescaled sum of squares that cannot be scaled back to the original data, and the unweighted R^2 was based on a sum of squares that violates the homogeneous variance assumption of least squares regression. But for those who subscribe to R^2-values, those in table 2 show a reasonable data fit to the model.

Confidence intervals, another method to assess goodness-of-fit, were examined. For each volume equation, confidence intervals were computed for two DRC classes corresponding to trees above and below the point of change (X_0). The median size tree was selected in each DRC class for actual computation. Then 95 percent confidence intervals were computed for predicting mean tree volume from varying numbers of sample trees. For example, if five multiple-stem junipers about 9 inches DRC (see first line of table 2) were measured for volume prediction, the expected true volume would lie in an interval ±36 percent of 2.5 ft^3 (1.6 to 3.4 ft^3). If 10 junipers of 9 inches DRC were sampled, the expected true volume would lie in a smaller interval of ±26 percent of 2.5 ft^3 (1.9 to 3.2 ft^3). A sample size of 20 junipers would further reduce the confidence intervals to 19 percent of 2.5 ft^3 (2.0 to 3.0 ft^3). Even larger sample sizes resulted in still smaller confidence intervals, but the interval reduction in relation to sample size diminished with the larger sample sizes.

The confidence intervals were computed as follows:

$$CI = 1.96\sqrt{MSE\,(1/WT/n + H)} \qquad (5)$$

where

CI = 95 percent confidence interval for a predicted mean

Table 2—Regression statistics from volume modeling

							Median statistics[1]					
				R^2				95 percent mean CI[2]				
Species group	DRC class	Basal stems	Number of trees	Weighted[3]	Unweighted[4]	Predicted volume	Median DRC	*n*=5	*n*=10	*n*=20	*n*=50	*n*=100
	Inches					*Ft^3*	*Inches*	*Percent*				
Juniper	<20	Multiple	203	0.91	0.82	2.5	9	36	26	19	13	10
	>20	Multiple	56	.91	.79	27.6	26	16	12	8	5	4
	<20	Single	262	.92	.88	1.4	6	34	25	18	13	11
	>20	Single	24	.92	.81	28.1	20	12	9	6	4	3
Pinyon	<12	Single	203	.89	.82	.9	7	39	30	23	19	17
	>12	Single	23	.89	.96	12.1	13	16	12	8	6	4
Oak	<16	Multiple	130	.91	.87	2.3	10	27	20	15	11	9
	>16	Multiple	9	.91	.77	11.9	18	15	11	8	6	4
	<16	Single	193	.90	.82	1.4	7	35	26	20	15	13
	>16	Single	18	.90	.89	21.7	19	14	10	7	5	4
Mesquite	<12	Multiple	168	.86	.81	1.3	8	38	28	21	16	14
	>12	Multiple	22	.86	.89	9.7	14	18	13	9	6	5
	<12	Single	123	.89	.88	.5	5	48	39	34	30	29
	>12	Single	8	.89	.92	11.6	14	13	9	7	6	5

[1] Statistics based on the median of the DRC class.

[2] Confidence intervals (CI) for mean predicted volume for several sample sizes for the median level of DSQH (roughly median DRC) in each DRC class. CI's are expressed as a percentage of predicted volume for each DRC class.

[3] Computed from weighted regression sum of squares with all tree sizes combined.

[4] Recomputed from data without consideration of regression weights.

MSE = mean squared error from weighted regression

WT = regression weight (DSQH raised to the –1.5 power)

n = desired number trees for confidence interval computations

H = leverage or $x_j(X'X)^{-1}x'_j$ as computed by SAS (1985, p. 663) for weighted regression.

DISCUSSION

All equations were compared graphically (fig. 2) for similarities and differences. The multiple-stem equations showed less volume for given DSQH values than did single-stem counterparts for all species groups. Of all the equations, single-stem mesquite appeared most different. However, extrapolation error may be the main cause, because few mesquite trees in the data exceeded a DSQH of 2.

Volume equations from this study (labeled Arizona) were then compared to equations from Hualapai/Havasupai (labeled H & H) and Fort Apache/San Carlos (labeled Apache) Indian Reservations (Chojnacky 1988; Chojnacky and Ott 1986). Also compared were Olson's (1940) and Andrew's (1988) mesquite equations and volume tables given by Barger and Ffolliott (1972, tables 30, 31, and 32).

The Barger and Ffolliott tables required "smoothing" of the tabulated data for graphic comparison. A spline interpolation (SAS 1985, p. 70) was used to plot tabulated data for Utah juniper (labeled B & F JUOS), alligator juniper (labeled B & F JUDE), pinyon (labeled B & F), and oak (labeled B & F).

Because some of the Barger and Ffolliott tables were based on diameter at breast height (d.b.h.), compatible graphic comparison required a conversion equation relating DRC to d.b.h. Data from single-stem trees measured on the San Carlos Indian Reservation (Chojnacky 1988) were used to develop the following equations:

$$\text{Juniper: } DRC = 2.62 + 0.8314\,(\text{d.b.h.}) + 0.0135\,(\text{d.b.h.}^2) \qquad n = 78,\ R^2 = 0.96 \tag{6}$$

$$\text{Pinyon: } DRC = 1.04 + 1.1181\,(\text{d.b.h.}) - 0.0029\,(\text{d.b.h.}^2) \qquad n = 102,\ R^2 = 0.94 \tag{7}$$

$$\text{Oak: } DRC = 0.41 + 1.3552\,(\text{d.b.h.}) - 0.0122\,(\text{d.b.h.}^2) \qquad n = 76,\ R^2 = 0.92 \tag{8}$$

Comparison of the juniper equations for single-stem trees showed large differences between Barger and Ffolliott's (B & F) work and the rest (fig. 3). However, these differences are probably due to volume definition standards. All equations, except Barger and Ffolliott's, included volume of all wood pieces at least 1-foot long and larger than 1.5 inches in diameter. Barger and Ffolliott's definition resulted in less volume per tree by including wood pieces with diameter standards similar to the others but omitting all pieces less than 4 feet long.

The pinyon volume equation from this study (Arizona) was found similar to the Hualapai/Havasupai (H & H) equation (fig. 4). Because Barger and Ffolliott's pinyon volume table appeared to be in error, a modification was made. In their table 31, diameter is defined at stump height for all trees, but it appears the volumes best correspond to d.b.h. for trees smaller than 10 inches and

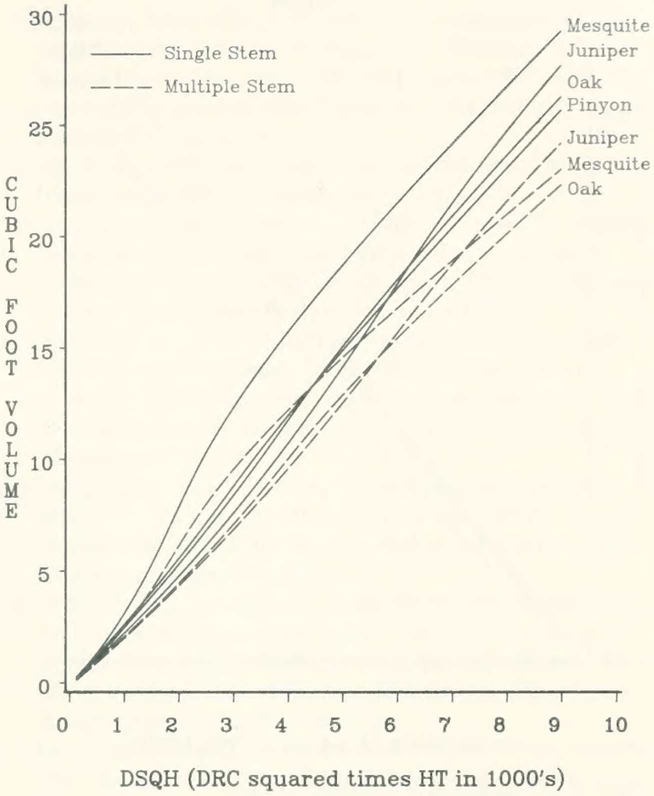

Figure 2—Comparison of the seven woodland volume equations from this study.

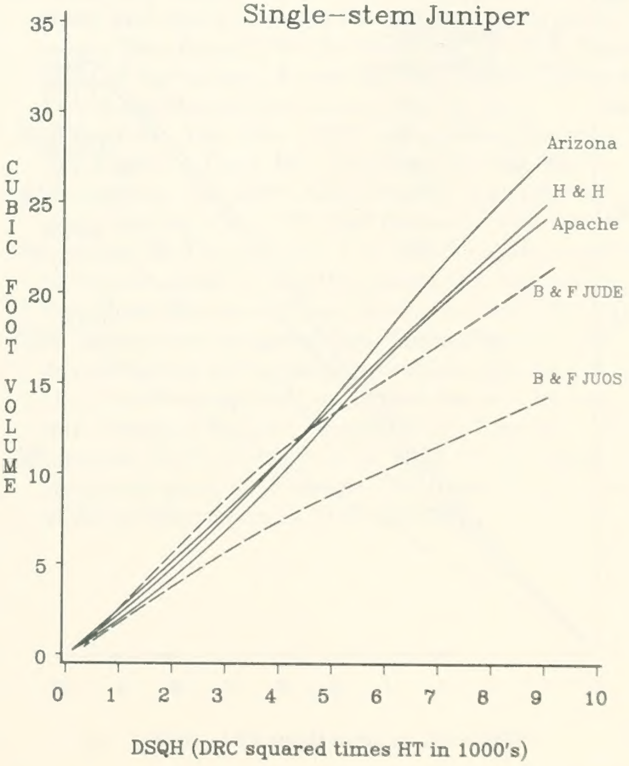

Figure 3—Comparison of this study's single-stem juniper equation (Arizona) with other single-stem juniper equations.

only correspond to diameter at stump height for trees larger than 10 inches. Equation 7 was used to obtain a corrected equation ("B & F" in fig. 4), which appeared comparable to the rest.

Comparison of the oak equations (fig. 5) showed single-stem equations from this study (Arizona) as similar to Fort Apache/San Carlos (Apache) single-stem equations. Apparent low predictions from the Barger and Ffolliott (B & F) equation probably resulted from their volume definition including wood only (the rest included wood and bark) and possibly from excluding branches.

Olson's mesquite equation predicted higher than the others (fig. 6). Perhaps a change in mesquite tree form over the past 45 years accounts for this difference between Olson's 1940 work and the recent single-stem equations. Andrew's equation was almost identical to the Arizona single-stem equation for small and average size trees but differed considerably for larger trees. Because Andrew's work included no large trees with a DSQH larger than 4, extrapolation error is a probable cause for this difference.

Comparison of the available Arizona woodland volume equations clearly showed differences. Those taken from Barger and Ffolliott always appeared to give the lowest volume predictions. In most cases, definition differences explained these discrepancies. Differences between this study's equations and the various Indian reservation equations showed no consistent pattern among the species groups.

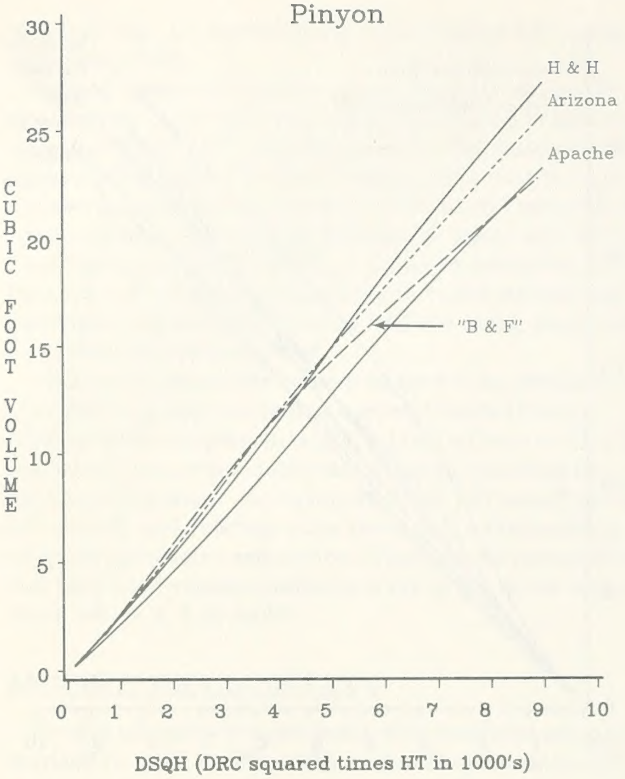

Figure 4—Comparison of this study's pinyon equation (Arizona) with other pinyon equations.

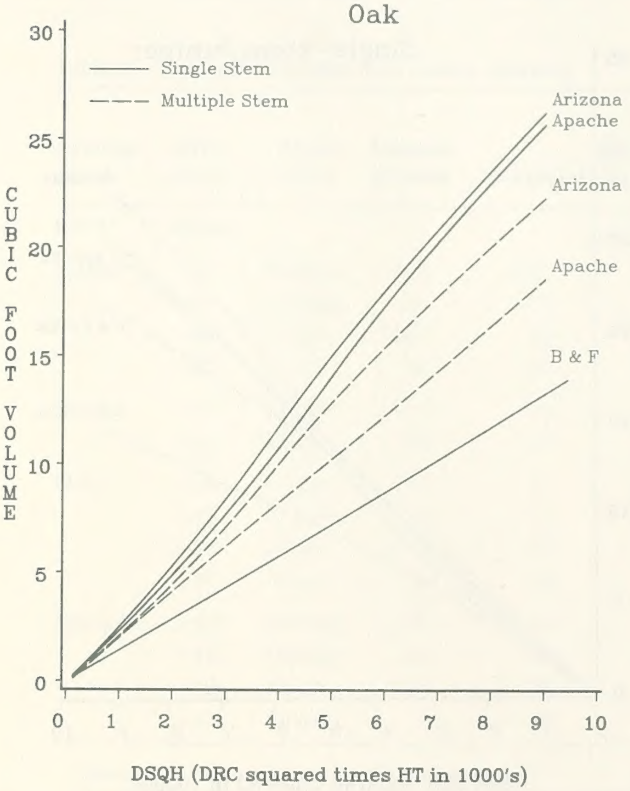

Figure 5—Comparison of this study's oak equation (Arizona) with other oak equations.

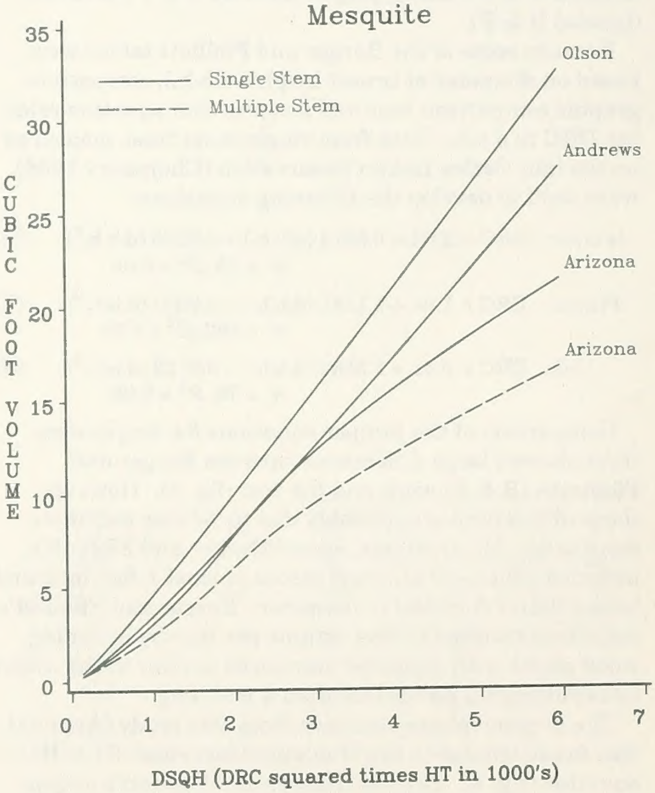

Figure 6—Comparison of this study's mesquite equations (Arizona) with other mesquite equations.

Recommendations on the "best" equations to use are difficult to make. As previously mentioned, definition differences account for some of the equation differences, but the unique developmental data for each equation should also be considered. Potential users should identify their desired volume definition standards and identify their geographic location for application, and then choose the equation that most closely fits their need. Users from the northern Arizona National Forests and from the Navajo Indian Reservation will have the most difficulty selecting equations because no recent woodland volume data have been published for their areas. Some of the 1940's data reported in the Barger and Ffolliott work came from Arizona and New Mexico National Forests, but precise documentation is lacking.

If choosing an appropriate woodland volume equation is an issue, doing visual volume estimation (Born and Chojnacky 1985) on a small sample of test trees (representing species and size diversity from the area of interest) will provide data for making a decision. The volume equation that best predicts the test data then should be used.

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APPENDIX

This appendix—tables 3 through 6—contains cubic foot volume tables and volume equations for juniper, mesquite, oak, and pinyon trees. Predicted volumes include wood and bark of all stems and branches larger than 1.5 inches outside-bark diameter. Both live and dead material are included. The range of the data is outlined on the tables, and numbers of trees sampled are summarized in the table margins. Use of the equations outside the diameter at root collar (DRC) and height ranges outlined on the tables is not recommended.

Table 3—Juniper outside-bark volume of stem and branch wood larger than 1.5 inches in diameter

DRC	Basal stems	Height (feet)																Number of trees
		6	8	10	12	14	16	18	20	22	24	26	28	30	32	35	40	
Inches		*Cubic feet*																
4	Multiple	0.1	0.1	0.2	0.3	0.3	0.4	0.5	0.5	0.6	0.7							12
	Single	.2	.2	.3	.4	.4	.5	.6	.7	.7	.8							68
6	Multiple	.3	.5	.6	.8	.9	1.1	1.2	1.4	1.5	1.7							33
	Single	.4	.6	.7	.9	1.1	1.2	1.4	1.6	1.7	1.9							51
8	Multiple	.7	.9	1.2	1.5	1.8	2.1	2.3	2.6	2.9	3.2	3.5	3.8	4.1				28
	Single	.8	1.1	1.4	1.7	2.0	2.3	2.6	2.9	3.2	3.5	3.9	4.2	4.6				37
10	Multiple	1.1	1.6	2.0	2.4	2.9	3.4	3.8	4.3	4.8	5.3	5.8	6.3	6.9				40
	Single	1.3	1.7	2.2	2.7	3.2	3.7	4.2	4.8	5.3	5.9	6.4	7.0	7.6				38
12	Multiple	1.7	2.3	3.0	3.7	4.4	5.1	5.8	6.5	7.3	8.1	8.9	9.7	10.5	11.4	12.6	14.9	29
	Single	1.9	2.6	3.3	4.0	4.8	5.6	6.4	7.2	8.1	9.0	9.9	10.8	11.8	12.8	14.3	16.9	32
14	Multiple	2.4	3.3	4.2	5.2	6.2	7.2	8.3	9.4	10.5	11.6	12.8	14.0	15.3	16.5	18.3	21.1	18
	Single	2.6	3.6	4.7	5.7	6.8	8.0	9.2	10.5	11.8	13.1	14.5	15.9	17.4	18.9	21.0	24.2	17
16	Multiple	3.2	4.4	5.7	7.0	8.4	9.9	11.4	12.9	14.5	16.1	17.7	19.2	20.7	22.0	24.1	27.3	21
	Single	3.5	4.9	6.3	7.8	9.4	11.0	12.8	14.6	16.5	18.4	20.3	22.0	23.7	25.3	27.5	31.1	14
18	Multiple		5.8	7.5	9.3	11.1	13.1	15.1	17.2	19.1	20.9	22.7	24.3	26.0	27.6	29.9	33.7	14
	Single		6.4	8.3	10.4	12.5	14.8	17.2	19.6	21.9	24.0	26.0	27.9	29.7	31.5	34.0	38.1	8
20	Multiple		7.4	9.6	11.9	14.4	16.9	19.3	21.5	23.6	25.7	27.7	29.6	31.5	33.3	36.0	40.5	15
	Single		8.2	10.7	13.4	16.3	19.3	22.1	24.7	27.1	29.4	31.6	33.7	35.7	37.7	40.7	45.5	11
22	Multiple		9.2	12.0	15.0	18.1	20.8	23.4	25.9	28.3	30.6	32.8	35.0	37.2	39.3	42.5	47.7	9
	Single		10.3	13.6	17.1	20.7	23.9	26.8	29.6	32.2	34.7	37.2	39.6	42.0	44.3	47.7	53.2	2
24	Multiple				18.5	21.7	24.7	27.6	30.3	33.0	35.6	38.2	40.7	43.3	45.8	49.5	55.6	13
	Single				21.2	24.9	28.3	31.5	34.5	37.4	40.3	43.0	45.8	48.5	51.1	55.0	61.5	1
26	Multiple				21.8	25.3	28.7	31.8	34.9	38.0	41.0	43.9	46.8	49.7	52.6	56.9	63.9	9
	Single				25.0	29.0	32.7	36.2	39.5	42.8	46.0	49.1	52.2	55.3	58.4	62.9	70.3	2
28	Multiple				25.2	29.0	32.7	36.3	39.8	43.2	46.6	49.9	53.3	56.6	59.9	64.8	72.9	4
	Single				28.8	33.1	37.1	41.0	44.7	48.4	52.0	55.6	59.1	62.6	66.0	71.2	79.8	4
30	Multiple				28.6	32.8	36.9	40.9	44.8	48.7	52.5	56.3	60.1	63.9	67.6	73.2	82.5	4
	Single				32.6	37.2	41.7	45.9	50.1	54.2	58.3	62.3	66.3	70.3	74.2	80.1	89.8	1
32	Multiple				32.1	36.8	41.3	45.8	50.1	54.5	58.8	63.1	67.3	71.6	75.8	82.2	92.7	3
	Single				36.5	41.5	46.4	51.1	55.8	60.4	64.9	69.4	73.9	78.4	82.8	89.5	100.5	0
35	Multiple				37.6	43.0	48.3	53.5	58.6	63.8	68.9	73.9	79.0	84.0	89.1	96.6	109.1	7
	Single				42.4	48.2	53.8	59.3	64.7	70.1	75.5	80.8	86.1	91.4	96.7	104.6	117.7	0
40	Multiple				47.4	54.2	60.9	67.6	74.2	80.8	87.4	94.0	100.6	107.1	113.6	123.4	139.7	0
	Single				52.9	60.1	67.2	74.2	81.2	88.1	95.0	101.8	108.7	115.5	122.4	132.6	149.6	0
Number of trees		34	51	97	93	78	74	57	20	19	11	2	4	1	3	0	1	545

Multiple-stem:

$$\text{Volume} = \begin{cases} -0.129 + 2.0255 \cdot X + 0.1011 \cdot X^2 & \text{for } X \leq 6 \\ 10.786 + 2.0255 \cdot X - 43.663/X & \text{for } X > 6 \end{cases}$$

where:

$X = \text{EDRC} \cdot \text{EDRC} \cdot \text{Height}/1{,}000$

Single-stem:

$$\text{Volume} = \begin{cases} -0.032 + 2.1076 \cdot X + 0.1454 \cdot X^2 & \text{for } X \leq 6 \\ 15.675 + 2.1076 \cdot X - 62.827/X & \text{for } X > 6 \end{cases}$$

where:

$X = \text{DRC} \cdot \text{DRC} \cdot \text{Height}/1{,}000$

Note: EDRC, DRC in inches and Height in feet.

Table 4—Mesquite outside-bark volume of stem and branch wood larger than 1.5 inches in diameter

DRC	Basal stems	Height (feet) 6	8	10	12	14	16	18	20	22	24	26	28	30	32	35	40	Number of trees
Inches		*Cubic feet*																
4	Multiple	0.2	0.3	0.3	0.4	0.5	0.5	0.6	0.7	0.8								12
	Single	.2	.3	.4	.4	.5	.6	.7	.8	.9								62
6	Multiple	.5	.6	.8	.9	1.1	1.3	1.5	1.7	1.9	2.1							49
	Single	.5	.7	.9	1.1	1.3	1.6	1.8	2.1	2.3	2.6							29
8	Multiple	.8	1.1	1.5	1.8	2.2	2.6	3.0	3.4	3.8	4.3	4.8						54
	Single	1.0	1.4	1.8	2.2	2.7	3.2	3.7	4.3	4.8	5.4	6.1						19
10	Multiple	1.4	1.9	2.5	3.1	3.8	4.5	5.3	6.1	6.9	7.6	8.3	8.9	9.5				34
	Single	1.6	2.3	3.1	3.9	4.8	5.8	6.8	7.8	8.9	9.8	10.7	11.5	12.3				11
12	Multiple	2.1	3.0	3.9	5.0	6.2	7.3	8.3	9.2	10.0	10.8	11.6	12.3	13.0	13.7	14.7	16.3	20
	Single	2.6	3.7	5.0	6.4	7.9	9.4	10.7	11.9	12.9	14.0	14.9	15.8	16.7	17.6	18.8	20.8	4
14	Multiple	3.0	4.4	5.9	7.5	8.8	9.9	11.0	12.0	13.0	13.9	14.8	15.7	16.5	17.4	18.6	20.6	11
	Single	3.8	5.6	7.6	9.6	11.3	12.8	14.2	15.5	16.7	17.9	19.0	20.1	21.1	22.2	23.8	26.3	3
16	Multiple	4.3	6.3	8.2	9.8	11.2	12.4	13.7	14.8	16.0	17.1	18.2	19.2	20.3	21.3	22.9	25.5	7
	Single	5.4	8.1	10.6	12.6	14.4	16.0	17.6	19.0	20.5	21.9	23.2	24.6	25.9	27.2	29.1	32.3	0
18	Multiple	5.9	8.3	10.2	11.9	13.5	15.0	16.4	17.8	19.2	20.5	21.8	23.1	24.4	25.7	27.6	30.8	2
	Single	7.5	10.7	13.2	15.4	17.4	19.2	21.0	22.8	24.4	26.1	27.8	29.4	31.0	32.6	35.0	38.9	3
20	Multiple				14.1	15.9	17.6	19.3	21.0	22.6	24.2	25.8	27.4	28.9	30.5	32.8	36.7	0
	Single				18.1	20.4	22.5	24.6	26.7	28.7	30.7	32.7	34.6	36.6	38.5	41.4	46.2	0
22	Multiple						20.4	22.4	24.3	26.3	28.2	30.1	32.0	33.8	35.7	38.5	43.2	0
	Single						26.0	28.5	30.9	33.3	35.6	38.0	40.3	42.6	45.0	48.4	54.2	0
24	Multiple						23.4	25.7	28.0	30.2	32.5	34.7	37.0	39.2	41.4	44.7	50.2	0
	Single						29.7	32.6	35.4	38.2	41.0	43.7	46.5	49.2	52.0	56.1	62.9	0
26	Multiple								31.9	34.5	37.1	39.7	42.4	44.9	47.5	51.4	57.9	0
	Single								40.2	43.5	46.7	49.9	53.2	56.4	59.6	64.4	72.3	0
28	Multiple								36.1	39.1	42.1	45.1	48.2	51.2	54.2	58.7	66.1	0
	Single								45.4	49.2	52.9	56.6	60.3	64.0	67.7	73.3	82.5	0
30	Multiple								40.6	44.0	47.5	50.9	54.4	57.8	61.2	66.4	75.0	1
	Single								51.0	55.2	59.5	63.7	68.0	72.2	76.5	82.8	93.4	0
32	Multiple								45.3	49.3	53.2	57.1	61.0	64.9	68.8	74.7	84.4	0
	Single								56.8	61.7	66.5	71.3	76.2	81.0	85.8	93.0	105.0	0
Number of trees		36	46	77	63	45	24	16	2	8	1	0	1	1	0	1	0	321

Multiple-stem:

$$\text{Volume} = \begin{cases} 0.020 + 1.8972 \cdot X + 0.5756 \cdot X^2 & \text{for } X \leq 2 \\ 6.927 + 1.8972 \cdot X - 9.210/X & \text{for } X > 2 \end{cases}$$

where:

X = EDRC•EDRC•Height/1,000

Single-stem:

$$\text{Volume} = \begin{cases} -0.043 + 2.3378 \cdot X + 0.8024 \cdot X^2 & \text{for } X \leq 2 \\ 9.586 + 2.3378 \cdot X - 12.839/X & \text{for } X > 2 \end{cases}$$

where:

X = DRC•DRC•Height/1,000

Note: EDRC, DRC in inches and Height in feet.

Table 5—Oak outside-bark volume of stem and branch wood larger than 1.5 inches in diameter

DRC	Basal stems	Height (feet)																Number of trees
		6	8	10	12	14	16	18	20	22	24	26	28	30	32	35	40	
Inches		*Cubic feet*																
4	Multiple	0.2	0.2	0.3	0.4	0.4	0.5	0.5	0.6	0.7	0.7							7
	Single	.2	.2	.3	.4	.5	.6	.6	.7	.8	.9							48
6	Multiple	.4	.5	.7	.8	1.0	1.1	1.3	1.5	1.6	1.8							22
	Single	.5	.6	.8	1.0	1.2	1.4	1.5	1.7	1.9	2.1							47
8	Multiple	.7	1.0	1.3	1.6	1.8	2.1	2.4	2.7	3.0	3.3	3.6						27
	Single	.9	1.2	1.5	1.9	2.2	2.5	2.9	3.2	3.6	4.0	4.3						39
10	Multiple	1.2	1.6	2.1	2.5	3.0	3.5	3.9	4.4	4.9	5.5	6.0	6.5	7.1				20
	Single	1.4	1.9	2.5	3.0	3.6	4.1	4.7	5.3	5.9	6.5	7.1	7.7	8.4				32
12	Multiple	1.8	2.4	3.1	3.8	4.5	5.2	6.0	6.8	7.6	8.4	9.3	10.1	11.0	11.8	13.0	14.8	30
	Single	2.1	2.9	3.7	4.5	5.3	6.2	7.1	8.0	8.9	9.9	10.9	11.9	12.9	13.8	15.2	17.3	17
14	Multiple		3.4	4.3	5.3	6.4	7.5	8.6	9.8	11.0	12.1	13.1	14.2	15.1	16.1	17.5	19.7	21
	Single		4.0	5.2	6.4	7.6	8.8	10.1	11.5	12.8	14.1	15.4	16.5	17.7	18.8	20.5	23.2	11
16	Multiple		4.6	5.9	7.3	8.8	10.3	11.8	13.2	14.5	15.8	17.0	18.2	19.4	20.5	22.2	25.0	3
	Single		5.4	7.0	8.6	10.3	12.1	13.8	15.4	17.0	18.5	19.9	21.3	22.7	24.1	26.1	29.5	6
18	Multiple			7.8	9.7	11.6	13.4	15.0	16.6	18.1	19.6	21.0	22.4	23.8	25.2	27.3	30.6	3
	Single			9.2	11.4	13.6	15.6	17.6	19.4	21.2	23.0	24.7	26.4	28.1	29.8	32.3	36.4	4
20	Multiple			10.0	12.3	14.4	16.4	18.3	20.1	21.9	23.6	25.3	27.0	28.7	30.3	32.8	36.8	5
	Single			11.8	14.4	16.9	19.2	21.4	23.6	25.7	27.8	29.9	31.9	34.0	36.0	39.0	43.9	3
22	Multiple			12.4	15.0	17.3	19.5	21.7	23.8	25.8	27.9	29.9	31.9	33.8	35.8	38.7	43.6	1
	Single			14.6	17.5	20.3	22.9	25.5	28.0	30.5	33.0	35.4	37.9	40.3	42.7	46.3	52.2	2
24	Multiple						22.8	25.2	27.7	30.0	32.4	34.8	37.1	39.4	41.7	45.2	50.9	0
	Single						26.8	29.8	32.7	35.6	38.5	41.4	44.3	47.1	49.9	54.2	61.2	0
26	Multiple						26.2	29.0	31.8	34.6	37.3	40.0	42.7	45.4	48.1	52.2	58.9	0
	Single						30.9	34.4	37.8	41.1	44.5	47.8	51.2	54.5	57.8	62.7	70.9	2
28	Multiple						29.8	33.0	36.2	39.4	42.5	45.7	48.8	51.9	55.0	59.7	67.4	0
	Single						35.3	39.3	43.1	47.0	50.9	54.7	58.6	62.4	66.2	71.9	81.4	0
Number of trees		25	42	61	70	53	38	26	13	3	8	1	4	2	0	3	1	350

Multiple-stem:

$$\text{Volume} = \begin{cases} -0.028 + 1.9545 \cdot X + 0.1400 \cdot X^2 & \text{for } X \leq 4 \\ 6.691 + 1.9545 \cdot X - 17.918/X & \text{for } X > 4 \end{cases}$$

where:

$X = \text{EDRC} \cdot \text{EDRC} \cdot \text{Height}/1{,}000$

Single-stem:

$$\text{Volume} = \begin{cases} -0.068 + 2.4048 \cdot X + 0.1383 \cdot X^2 & \text{for } X \leq 4 \\ 6.571 + 2.4048 \cdot X - 17.704/X & \text{for } X > 4 \end{cases}$$

where:

$X = \text{DRC} \cdot \text{DRC} \cdot \text{Height}/1{,}000$

Note: EDRC, DRC in inches and Height in feet.

Table 6—Pinyon outside-bark volume of stem and branch wood larger than 1.5 inches in diameter

DRC	Basal stems	Height (feet)																Number of trees
		6	8	10	12	14	16	18	20	22	24	26	28	30	32	35	40	
Inches		*Cubic feet*																
4	Single/ Multiple	0.2	0.3	0.3	0.4	0.5	0.6	0.7	0.8	0.8	0.9	1.0	1.1					84
6	Single/ Multiple	.5	.7	.9	1.1	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8				43
8	Single/ Multiple	.9	1.3	1.6	2.0	2.3	2.7	3.0	3.4	3.8	4.1	4.5	4.9	5.3	5.7			36
10	Single/ Multiple		2.0	2.6	3.2	3.7	4.3	4.9	5.6	6.2	6.8	7.5	8.1	8.8	9.5	10.4		29
12	Single/ Multiple			3.9	4.7	5.6	6.5	7.4	8.4	9.4	10.3	11.2	12.1	12.9	13.8	15.0	17.0	18
14	Single/ Multiple			5.4	6.7	7.9	9.3	10.5	11.7	12.9	14.0	15.2	16.3	17.3	18.4	20.0	22.6	10
16	Single/ Multiple				9.0	10.7	12.3	13.8	15.2	16.7	18.1	19.4	20.8	22.2	23.5	25.5	28.9	2
18	Single/ Multiple				11.6	13.6	15.4	17.2	19.0	20.7	22.4	24.1	25.8	27.5	29.2	31.7	35.9	1
20	Single/ Multiple				14.3	16.6	18.7	20.9	23.0	25.1	27.2	29.3	31.3	33.4	35.5	38.5	43.6	1
22	Single/ Multiple							24.9	27.4	29.9	32.4	34.9	37.4	39.9	42.3	46.0	52.2	0
24	Single/ Multiple							29.2	32.2	35.1	38.1	41.0	44.0	46.9	49.8	54.2	61.5	1
26	Single/ Multiple							33.8	37.3	40.8	44.2	47.6	51.1	54.5	57.9	63.0	71.6	1
28	Single/ Multiple							38.8	42.8	46.8	50.8	54.8	58.7	62.7	66.7	72.6	82.5	0
Number of trees		10	30	45	35	25	17	22	12	10	10	2	3	1	1	3	0	226

$$\text{Volume} = \begin{cases} -0.060 + 2.5139 \cdot X + 0.1466 \cdot X^2 & \text{for } X \leq 3 \\ 3.898 + 2.5139 \cdot X - 7.917/X & \text{for } X > 3 \end{cases}$$

where:

$$X = \begin{cases} \text{DRC} \cdot \text{DRC} \cdot \text{Height}/1{,}000 & \text{for single-stem trees} \\ \text{EDRC} \cdot \text{EDRC} \cdot \text{Height}/1{,}000 & \text{for multiple-stem trees.} \end{cases}$$

Note: EDRC, DRC in inches and Height in feet.

Chojnacky, David C. 1988. Juniper, pinyon, oak, and mesquite volume equations for Arizona. Res. Pap. INT-391. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 11 p.

Volume prediction equations have been developed for Arizona's juniper, pinyon, oak, and mesquite woodland tree species. The equations require measurements of total tree height and tree diameter near the root collar. Results are presented in equation and tabular formats. Volume equation construction, volume equation reliability, and comparison of the results with other studies are discussed.

KEYWORDS: *Juniperus, Pinus edulis, Prosopis, Acacia, Olneya, Quercus,* volume table, Cook's-D, weighted regression

INTERMOUNTAIN RESEARCH STATION

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